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FRONTIERS IN ATOMIC ENERGY RESEARCH

SUMMARY-ANALYSIS OF HEARINGS HELD ON MARCH 22, 23, 24, AND 25, 1960

BEFORE THE

SUBCOMMITTEE ON RESEARCH AND DEVELOPMENT

OF THE

JOINT COMMITTEE ON ATOMIC ENERGY

CONGRESS OF THE UNITED STATES

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CONTENTS

	Page
Introduction	1
Background of hearings	2
Highlights of presentations	4
A. Peaceful uses of nuclear explosives (Plowshare program)	4
B. Controlled thermonuclear reactions (Sherwood program)	6
C. Advanced reactor applications	9
D. Space propulsion and power	11
E. Direct energy conversion and solar energy systems	15
Conclusions	18

FRONTIERS IN ATOMIC ENERGY RESEARCH

Introduction

In the two decades since the energy in the atom was discovered, fates of nations and ideologies have become dependent on technological leadership in research. Preeminence in this field is vital to us as a nation. We must be ever mindful that the United States and the free world are in a real struggle with the Soviets for scientific and technical leadership.

The past record of this committee and its ability to recognize and support the work of AEC laboratories in the field of atomic energy are well known. In its efforts on behalf of our advancing technology, the committee has held extensive hearings on basic research in the nuclear field, and, on many occasions, on specific development programs or on specialized aspects of atomic energy technology.

Two years ago, the committee held a series of hearings on basic research in the physical sciences at which working scientists from atomic energy laboratories throughout the country presented their experiments and ideas in the fields of basic knowledge relating to nuclear energy. How to provide the utmost encouragement for work in basic fields was explored and the conclusion was reached that vigorous and dependable support of the best scientists is the key to continued effective basic advances.

Almost continuously the committee holds hearings on specific development problems in the field of atomic energy. These hearings are concerned with how to provide support and effective direction to the many short-term programs designed to provide applications of nuclear energy within a decade.

It has become increasingly evident that there is a highly significant gap between these areas of basic research and short-term development projects; this is the transitional phase of planning and action for entirely new developments from basic ideas, the frontiers of atomic energy technology. It is evident that the long-range applications of nuclear technology must come through a process that starts with the basic knowledge and proceeds through planning and purposeful action into what will become the short-range development projects a decade or two hence.

It is this transition that clearly requires more attention from all forward-looking people concerned with technology, for the transition does not come about by itself. It requires the vision of imaginative scientists. It requires resources in men and laboratory facilities and money. It requires an atmosphere in which the seedling projects of faraway applications can compete effectively with the pressures, schedules, and requirements of short-range urgent work. Finally and most importantly the effective transition from basic idea to serious development requires thoughtful planning and thorough examination of basic

fields to assure that the ideas leading to faraway application are being found and that their implications are being recognized.

Too often in the past the conversion of ideas to application has been haphazard. The desperate developments of military applications have been so fruitful not because of an inherent quality in the military uses but because the pressures of war or defense preparation have given the impetus to start the developments, where peaceful motivations would not have sufficed. Occasionally work in a peaceful context on a long-range application starts through general recognition of promise in a possibility; more often it starts through the long-painful, often discouraging promotional efforts of a single man or of a small dedicated group.

If we are to maintain our technology in a position of world leadership, we must improve on these disorganized and undependable methods for encouraging a long view in technology. As a first step, the country must call on men of scientific vision to explore and describe the areas showing promise. With their views in mind, the Congress, the executive branch and the public (including universities and industry) can proceed to develop perspective and considered judgment on decisions to be made for opening what may be the most stimulating frontiers in the history of this Nation.

Background of Hearings

Recognizing the need for a serious exploration of areas of technology that show long-range promise of fruitful application but may not be under adequate development because of short-term pressures, the Subcommittee on Research and Development scheduled a series of hearings in March in which leading scientists from industry, universities, and Government laboratories were invited to present their ideas and predictions on potential long-range applications in fields relating to atomic energy. The hearings were held on March 22, 23, 24, and 25, 1960.

It is the primary aim of the subcommittee to compile this material for the use of Congress, the executive branch, and the public in developing and implementing a national policy for improvement of the conditions under which long-range work can be carried out in the Nation's technological effort. This aim has been developed in recognition of the fact that our future technological position on the world scene depends on the Nation's action to bring about entirely new developments.

The hearings were patterned on similar hearings held by the subcommittee in previous years on atomic research in the fields of biology, medicine, agriculture, and physical research.

The schedule of the hearings, including the material covered and the names of the scientists making the presentations, was as follows:

Tuesday, 2 p.m., March 22, 1960

SESSION OF THE JOINT COMMITTEE ON ATOMIC ENERGY SUBCOMMITTEE ON RESEARCH AND DEVELOPMENT HEARINGS ON FRONTIERS IN ATOMIC ENERGY RESEARCH

Introductory remarks	John A. McCone, Chairman, Atomic Energy Commission.
General introduction to frontier hearings	Dr. Henry de Wolf Smyth, Princeton University.

PEACEFUL USES OF NUCLEAR EXPLOSIVES (PLOWSHARE PROGRAM)

I. General introduction and advanced research applications.	Dr. Harold Brown, Lawrence Radiation Lab.
II. Industrial chemicals and isotope production.	Dr. Philip Abelson, Carnegie Institute.
III. Mineral recovery:	
(*a*) Tar sands	William J. Travers, vice president, Richfield Oil Corp.
(*b*) Oil shales	Do.
(*c*) Mining	Dr. James Boyd, Kennecott Copper Corp.
IV. Summary	Dr. Edward Teller, Director, Lawrence Radiation Laboratory.
V. Energy production and recovery Excavation Water Resource Development	Dr. G. W. Johnson, Lawrence Radiation Laboratory.
(*a*) Aquifers.	
(*b*) Dams and lakes.	

Wednesday, 10 a.m., Mar. 23, 1960

CONTROLLED THERMONUCLEAR REACTIONS (SHERWOOD PROGRAM)

I. Introduction and general review of the Sherwood program.	Dr. Paul McDaniel, Division of Research, Atomic Energy Commission. Dr. Arthur E. Ruark, Atomic Energy Commission.
II. Los Alamos Sherwood research program.	Dr. James L. Tuck, Los Alamos Scientific Laboratory.
III. Lawrence Radiation Laboratory	Dr. Richard F. Post Lawrence Radiation Laboratory.
IV. Oak Ridge National Laboratory	Dr. Arthur H. Snell, Oak Ridge National Laboratory.
V. Princeton University	Dr. Melvin B. Gottlieb, Princeton University.

Thursday, 10 a.m., Mar. 24, 1960

ADVANCED REACTOR APPLICATIONS

I. Survey of advanced concepts	Dr. Bernard I. Spinrad, Argonne National Laboratory.
II. General applications	Dr. David B. Hall, Los Alamos Scientific Laboratory.
III. Chemical applications	Mr. Bernard Manowitz, Brookhaven National Laboratory.
IV. Coal processing	Mr. Harry Perry, Bureau of Mines, Department of Interior.
V. Seminar:	
Dr. Karl Cohen, General Electric Co.	Dr. Chauncey Starr, Atomics International.
Dr. David B. Hall, Los Alamos Scientific Laboratory.	Dr. Alvin Weinberg, Oak Ridge National Laboratory.
Mr. Bernard Manowitz, Brookhaven National Laboratory.	Dr. Walter H. Zinn, Combustion Engineering Co.
Dr. Bernard L. Spinrad, Argonne National Laboratory.	Mr. John W. Simpson, Westinghouse Electric Co.

Thursday, 2 p.m., Mar. 24, 1960

SPACE PROPULSION AND POWER

I. Nature of space challenge and general space propulsion concepts.	Dr. Krafft Ehricke, Convair Astronautics.
II. Rover project and nuclear explosives for propulsion.	Dr. Raemer Schreiber, Dr. Stanislaw Ulam, Los Alamos Scientific Laboratory.
III. Electric (ION) propulsion	Dr. Robert H. Fox, Lawrence Radiation Laboratory.
IV. Advanced auxiliary power systems	Dr. Robert E. English, National Aeronautics and Space Administration.
V. Nuclear auxiliary power systems	Dr. J.R. Wetch, Atomics International.

Friday, 10 a.m. Mar. 25, 1960

DIRECT ENERGY CONVERSION AND SOLAR ENERGY SYSTEMS

I. Direct conversion concepts	Mr. Paul H. Egli, Head of Crystal Branch, Naval Research Laboratory.
II. Thermionic cell development	Dr. George M. Grover, Los Alamos Scientific Laboratory.
III. Development of solar power devices for industrial and domestic uses.	Dr. George O. G. Löf, solar energy consultant, Resources for the Future, Denver, Colo.
IV. Solar energy applications in less developed nations.	Dr. J. A. Duffie, University of Wisconsin.

Highlights of Presentations

A. PLOWSHARE

"Plowshare" is the name given to the AEC program for developing peaceful uses of nuclear explosives. The proposed applications are listed below along with a description of each.

1. Research studies

Studies made at Los Alamos and Livermore indicate that elements of very high atomic number and some neutron-rich unstable lighter elements can be obtained in larger quantities by nuclear explosions than in any other way. The study of these artificial elements can reveal a great deal concerning nuclear structure. Fission resonances of U^{235} may be better studied by nuclear explosions as well as neutron spectroscopy experiments, seismology studies and other similar studies being possible.

2. Chemical and isotope production

A megaton detonation releases energy equivalent to one thousand trillion calories which is the amount of energy produced when 150,000 tons of coal are burned. Another feature of interest in this context is that extremely high temperatures are available in these nuclear explosions which effectively produce unprecedented quantities of matter in the form of free atoms. Such compounds as lime can be formed in a nuclear explosion and the stored energy (chemical) can be tapped gradually.

Temperatures of 10,000° F. were mentioned which are available to form simple compounds. Elements such as aluminum and silicon will quickly form certain oxides not ordinarily existing at normal

temperatures. At progressively lower temperatures (below 10,000° F.) other chemical combinations occur. Depending on the composition of the original matter vaporized in the detonation, new compounds formed may be quite different from those originally present.

3. Mineral recovery

Project Oilsand is proposed to use nuclear energy underground to release large oil deposits trapped in oil sand formations which are located in the Athabaska area of Alberta, Canada. Geologic and stratigraphic data from wells drilled in the Athabaska area indicate oil sands of at least 17,000 square miles in area which may contain 600 billion barrels of oil. A certain amount of research is necessary for such things as degree of radioactive contamination, mechanism of heat distribution to release the oil in the cavity, cracking the oil, etc.

Mining by use of nuclear explosions has the following possible approaches:

1. Breaking and removal of overburden before the mining of the ore body is undertaken.
2. Breaking of the ore in preparation for open-pit mining.
3. Breaking of ore and cap rock to facilitate block caving.
4. Breaking of ore to permit the circulation of solutions through the broken ore in order to extract the valuable minerals chemically.
5. Breaking of oil shale to permit its being retorted underground without the necessity of mining.

Experimentation on barren rock which has the same physical characteristics as the ore bodies would have to be done first to avoid gambling with our natural resources.

4. Energy production and recovery

Various ideas have been suggested for the conversion of the energy released in nuclear explosions into usable heat. The simplest scheme is based on the observed results from underground nuclear explosions that about one-third of the energy released is deposited in melted rock at high temperatures. It is proposed that nuclear explosions in salt domes would produce large pools of melted salt which then could be tapped for this stored energy by use of a driving fluid such as water in pipes. The resulting steam or hot gas could be used for power purposes. Another method would be to use nuclear detonations to release geothermal energy which could also be exploited by using a transfer fluid.

5. Excavation

The approach of using nuclear explosions for earth moving purposes seems to offer the most promise. The areas in which the excavating potentialities can be exploited are the construction of harbors, canals, and other waterways and the damming of rivers or streams and similar projects.

From the standpoint of economics the AEC published data in September 1958 concerning costs of usable devices for nuclear detonations (Ref. UCRL 5253 "Industrial Uses of Nuclear Explosives"). A 30-inch diameter device (fission) with the energy equivalence (yield) of a few thousand tons of chemical explosive would cost about $500,000 for fabrication and firing when made in small numbers. For similar conditions but with several tons or kiloton yield the cost would be about $750,000. Other costs and sizes are scaled accordingly.

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It was also noted that in the event of multiple firing in the same location or in using large numbers of devices the charge for firing would be substantially reduced. These costs do not include preparation of site or studies for industrial utilization. It is estimated that costs for excavating harbors and canals which do not require great depths would be about a factor of 10 less than conventional costs.

A chemical explosives cratering program is proposed to be done first to develop scaling laws, dependence of crater dimensions on depth of burial and nature of the medium, determine placement of multiple charges and other effects. This would be followed by a nuclear explosives cratering program to correlate these results with what was learned in the chemical explosives studies, to obtain data on the effectiveness of containment and localization of radioactivity.

6. Water resource development

The technique of using nuclear explosives may in turn be applied to developing water resources either by direct cratering or by collapsing canyon walls to build earth dams. Storage of water underground and uniting permeable zones with impermeable ones are also proposed. The question of takeup and migration of radioactivity in water needs to be thoroughly investigated at each site prior to setting off an explosion.

B. CONTROLLED THERMONUCLEAR RESEARCH

The controlled thermonuclear program or Project Sherwood is research conducted toward production of fully controlled power and heat from the nuclear fusion of the heavy hydrogen isotopes—deuterium or tritium. In the United States the program is being spearheaded at four major laboratories—Princeton, Oak Ridge, Livermore, and Los Alamos. There are also 16 small contracts at various other installations under which research is being conducted.

The main objective of this research is to confine a very hot and tenuous gas or plasma in a vacuum environment with the aid of a strong magnetic field. This plasma consists of electrons and these nuclei from which they were stripped. The problems are to heat this plasma initially and to confine it in a tube or container long enough to permit collisions of nuclei in great enough numbers, to achieve thermonuclear temperatures and the consequent fusion of nuclei and release of energy. The magnetic fields are intended to concentrate the plasma and to prevent it from contacting the walls of the container.

These hearings bring up to date the status of this research since the 1958 Geneva Conference on Peaceful Uses. It is apparent that the three major programs in the United Kingdom, U.S.S.R., and United States are going in the same direction generally although the emphasis has been different. There are also organized programs in Australia, Denmark, France, West Germany, Italy, Japan, The Netherlands, and Sweden.

The United States has about 350 scientists working in this field. In the United Kingdom and Western Europe there are about the same number and the U.S.S.R. effort is comparable with either the United States or the United Kingdom and Western Europe programs.

Dr. Ruark, Chief, Controlled Thermonuclear Branch, Research Division, U.S. Atomic Energy Commission, pointed out in these hearings that "our present job is to light the nuclear fire" as a first objective. The second objective will be to design and build a pilot

plant yielding net power. The attainment of thermonuclear temperatures in a few years would not mean that fusion power had been developed.

The general belief is that 10 to 20 years might be needed thereafter for the development of the first fusion powerplant. However, despite the amount of data accumulated to date in this field there is no certainty yet as to the feasibility of developing thermonuclear powerplants.

The major U.S. research divides into five areas as follows:

1. Stellarators: These are endless, hollow tubes similar to hollow doughnuts with coils of magnets around the tubes. This is the approach used at Princeton.

2. Injection into magnetic mirrors: Particles are injected at high energies into straight magnetic bottles. This work is being done at Livermore and Oak Ridge.

3. Self confinement methods (pinch effect): Strong currents are passed through the gas confined by the magnetic field of these currents. These methods are practiced at Los Alamos, Berkeley, Livermore, and the Naval Research Laboratory.

4. Astron: Currents of very fast electrons are employed to confine and heat the plasma and is being studied at Livermore.

5. Spinning plasmas: In this case both electric and magnetic fields are employed. Small efforts on this are proceeding at Los Alamos and Berkeley.

The following represents the work as it was presented for the four major U.S. laboratories.

Los Alamos

As an introduction it was pointed out that the thermonuclear approach to power is potentially less hazardous than the uranium-reactor approach because of the absence of fission products.

The approach to the work at Los Alamos centers around many small devices. The Scylla I device exhibited at Geneva has had a thermonuclear reaction lasting 0.9 microsecond. Scylla II has been similarly successful in producing thermonuclear temperatures for 7 microseconds. It was pointed out however that it is very unlikely to lead to any kind of economic power device.

The picket fence or cusped geometry is another approach being studied because of its great hydromagnetic stability. High density plasmas have been contained for 30 microseconds by means of entropy trapping techniques.

Lawrence Radiation Laboratory

The highlights of certain particular approaches at the Lawrence Radiation Laboratory were presented rather than a detailed description of the work. The program is carried out at both the Berkeley and Livermore branches of this laboratory. There are about 50 scientists involved in the total program. About 15 percent of the work is done at Berkeley with one group carrying out several small-scale experiments on fundamental plasma diffusion and rotation effects. The other 85 percent of the work is at Livermore with three groups studying problems of confinement and stability and are, namely, the pinch research, the astron, and mirror machine groups.

A number of different kinds of instabilities have been predicted theoretically where the plasma is not subject to simple hydromag-

netic instabilities. By means of developing critical experiments to eliminate these one by one it is hoped that ultimately successful solutions to all these problems will be attained.

1. *Pinch research.*—It has been theoretically predicted that many of the desirable confinement properties of the toroidal pinch can be retained by using a solid conductor for the central portion of the pinch current. Small experiments have proven the feasibility of suspending a hard-core device called a levitron by means of magnetic levitation within a chamber. A medium-sized levitron (12-inch bore) is now being readied for tests of plasma confinement and stability.

2. *Astron research.*—The key feature here is the use of very high energy electrons (called the E-layer) to be maintained within a long cylindrical evacuated chamber. The initial phase is the generation of the confining field. It then must also perform the important function of ionization and heating. The basic question to be answered in a few years is whether or not a stable, field-reversing E-layer can be produced. This is theoretically difficult to predict so experimental investigations must be done.

3. *Mirror Machine research.*—The Table Top (magnetic mirror experiment) results are very encouraging but do not constitute a proof that plasmas in which the ions (instead of electrons) are very hot would also be stably confined in a mirror machine. Achieving such a plasma is therefore the most important next step. Two approaches are being explored.

In Toy Top (magnetic mirror experiment) the magnetic compression principle will again be used but in several successive stages. The plasma will be compressed by means of moving magnetic mirrors into a series of confinement chambers of ever-decreasing diameter. The first section of this machine has been successfully tested and construction of the complete machine is underway.

Another program of interest is the investigation of cryogenic coils (which produce very low temperatures) and their applications to thermonuclear power use. By using high purity aluminum or sodium metal encapsulated in stainless steel tubes, coils could be made which could result in a large reduction in both power requirements and in dollar costs of high magnetic fields. This is due to the very low electrical resistance at low temperatures obtained with pure metal conductors.

Oak Ridge National Laboratory

In the DCX machine, hot plasma is accumulated in a magnetic containing volume by injecting a continuous stream of ions from an outside source. Molecular ions are injected since the charged particles (atomic ions) build up inside and form the desired plasma. Charge exchange presently prevents the density from building up to a value required for a thermonuclear reaction. It is hoped that by putting in enough ions in a high vacuum the interior of the plasma will be protected by the outer layers. The gas molecules coming in will thus charge exchange before penetrating far into the trapped circulating beam.

The carbon arc producing the ions is also responsible for large charge exchange losses because of the repetitious circulation of atomic ions passing through it and the excess electrons on the carbon atoms which perpetuate this charge exchange. Other arcs are being investi-

gated including the hydrogen arc. This arc is most promising since there are no electrons to cause charge exchange. The main disadvantage in using hydrogen is that much larger vacuum pumps must be used due to the large volumes of hydrogen being fed into the system.

Another method of resolving the charge exchange problem is to have multiple passes of the molecular ion beam through the arc. This offers at present the most encouraging way to surmount the charge exchange problem.

Princeton University

The stellarator program at Princeton consists of a number of devices being studied for containment of a hot gas or plasma in a magnetic field. There are five stellarators in operation which have somewhat different functions.

One phenomenon being studied is called pump-up, which is the high speed movement of the plasma to the wall of the containing vessel. The gas moves to the container vessel wall in about a ten-thousandth of a second, in general. The main reasons for this are being sought.

One major program at Princeton is the model C stellarator, which is nearing completion of fabrication. It consists of a torus with spiraling windings around it to produce a stable configuration. The torus will be 7 feet in diameter and the tube that goes inside will be 8 inches in diameter. It will be used to study basic plasma behavior experimentally.

C. ADVANCED REACTOR APPLICATIONS

The aims of this phase of the frontiers hearings were to attempt to perceive the ultimate goals of nuclear energy somewhat more clearly. An overall look at what seems promising as well as certain specific applications were presented.

Survey of advanced concepts

The classification of nuclear systems were presented according to the particular characteristics attributed to fission energy rather than by reactor type or application. These characteristics are:

1. *Intrinsic low cost of nuclear fuel as mined.*—This was represented as the primary advantage of nuclear reactors. Evaluation of power reactors by reactor category rather than fuel category seems to obscure this fact. It was concluded that power reactor technology should emphasize using the nuclear fuel in the most economical fuel cycle.

2. *Unique compactness of nuclear fuel.*—One gram of U^{235} is capable of producing about 24,000 kilowatt-hours of heat. This capability coupled with the compact structure of nuclear reactors offers various advantages for applications where fuel or system size and weight restrictions may be suggested. Compact power units for the Arctic and Antarctic are examples of utility of this characteristic.

3. *Nuclear fuel does not need any other material for its burning.*—Most common chemical fuels such as coal or oil use more oxygen by weight than the fuel itself. The nuclear submarine is an example of an application which takes advantage of the independence of the nuclear reaction on the presence of air. Applications in space or other airless environments are foreseen by this feature.

4. *The controllability of nuclear wastes.*—The degree to which radioactive waste from nuclear power reactors have been contained compared to the containment of wastes from fossil-fueled plants may provide an advantage for nuclear plants over conventional plants. The increase of carbon dioxide in the atmosphere from fossil energy sources may perhaps be a more disturbing factor in our environment than the release of radioactive wastes may be. For this reason it was stated that ultimately nuclear power may be preferred for large urban centers over conventional plants.

5. *The ability of nuclear energy to deliver sharp and controllable pulses of energy.*—The Plowshare application was noted and also such applications as conversion of this pulsed energy directly into mechanical shocks for pulse jet propulsion or using the high temperatures and pressures for selected chemical processes.

6. *High temperature nuclear heat.*—Nuclear heat is limited only to the extent that we can retain materials in solid or liquid form. Chemical and metallurgical processes may be further enhanced because of the attainment of temperatures higher than from chemical sources.

7. *The ability of nuclear fission to produce ionization.*—This is considered as perhaps the most unique feature of nuclear energy. Virtually all of the energy of fission goes into ionization of materials surrounding it and heat appears only when these ions are recombined.

8. *A reactor as a source of radiation is a well-known research tool.*—The advantages of using reactors for research purposes are that it can lead us as in the past in extremely useful and fruitful directions and historically, an overwhelming number of technological advances in other applications are pioneered by such use. For example, the transmutation of the elements using nuclear energy can be suggested. Useful applications of a number of isotopes produced by reactors have already been developed and the production and use of additional new isotopes are being investigated.

9. *Breeding as a reactor feature.*—This is recommended to better exploit available uranium and thorium ores. Among the various speakers there seemed to be a sharp difference of opinion as to the immediacy of the need for breeder reactor development.

General applications

The statement was made that reactor power used for process heat has not received all the attention it may merit in the long-range picture. But it was noted that process heat reactors are in competition with byproduct fuels which are inherently low in cost.

The application to oceanographic research was mentioned where a small reactor powerplant with a long fuel life contained in a pressure vessel could be utilized. Present conventional equipment lacks mobility, endurance, and sufficient power for undersea exploration.

An important source of minerals is available in the salts and sedimentary precipitates of the ocean. Use of nuclear explosives to break up the mineral belts on the ocean floor and hydraulic lifts or jet pumps all might utilize nuclear energy for this exploitation.

Chemical applications

It was indicated that nuclear reactors could possibly be used for producing industrial chemicals although it was recognized that the technological problems are considerable relative to the applications.

Problems in the utilization of fission fragment energy for chemical production are—

Absorption of fission fragments in the desired media as well as loss of them leaving their origin demands a new fuel technology for such reactor systems.

Contamination of chemical products entails added costs for decontamination before marketing.

A need must exist for a large tonnage market of product because of the large quantities of energy available in the reactors of the type which must be utilized.

Radioactive corrosion products will be formed.

Possible chemical products which may be made with chemo-nuclear reactors are—

Nitrogen dioxide.
Nitric acid.
Ammonium nitrate.
Argon.
Ethylene glycol.
Phenol.

Three types of fuel have been considered, namely, a glass wool containing a high concentration of uranium oxide dissolved in the glass, an array of flat ribbons on which a thin coating of uranium oxide is plated and thirdly a dispersion of very fine uranium oxide particles in a circulating gas.

The results of an economic analysis made for small and large plants today are—

1. At the present state of our knowledge there is not much difference in cost of the reactors using the different types of fuels described.

2. None of the chemo-nuclear systems are competitive with present day fixed nitrogen plants using fossil fuel at 40 cents per million B.t.u.

Coal processing

This work has been divided into three parts: (1) Studies on the irradiation of coal, (2) high temperature reactors for process heat, and (3) the potential application of radioisotopes in the coal industry.

The work on the irradiation of coal has consisted of experiments by the Bureau of Mines and others to determine the effect of radiation on the physical and chemical properties of various kinds of coal. Only minor effects have been noted.

The Bureau of Mines is conducting research for a process heat reactor. Gasification of coal to make carbon monoxide and hydrogen could be used for the production of organic chemicals and also to serve as the basic raw material for substitutes for natural gas and petroleum products. Carbonization and metallurgical processing are other possible applications. The temperatures being considered are far beyond those for the power reactor program. The objectives are to develop a reactor capable of heating helium to a range of 2,000° to 2,500° F. and to transfer such heat to process steam.

D. SPACE PROPULSION AND POWER

A view of future applications of atomic energy would necessarily include its use in space activities. The fourth session of the subcommittee was devoted to exploring how nuclear activities of the present and future will contribute to meeting the challenge of space

exploration and travel, and how such activity will enhance this Nation's chances for world leadership in space.

The most important requirement for successful space accomplishment is concentrated power from small and lightweight packages for both propulsion and auxiliary power systems. Nuclear energy is thus the key to the requirements for space exploration and operation.

Our capabilities in space propulsion for the immediate future hinge upon extending current know-how in chemical propulsion by scaling liquid and solid propellant engines to high thrust sizes or by clustering engines of existing sizes. Most witnesses seemed to agree that the Soviets have done comparatively well in achieving a high thrust capability although there remains the unsettled question of the degree of sophistication and reliability of Soviet rocket propulsion plants. The United States is, however, rapidly advancing toward a high thrust capability as exemplified by developments such as the Saturn booster and the F–1 engine.

But the question of where we stand vis-a-vis the Soviets in chemical propulsion capability as of today is of minor importance when compared to the question of what our relative future capabilities might be. Chemical burning for space propulsion has discrete practical limitations and any consideration of interplanetary space flight, manned or unmanned, must utilize the gains offered by nuclear energy. As one witness so vividly stated:

* * * The nuclear engine is for astronautics what the combustion engine is for aeronautics * * *

This conclusion is readily arrived at when one considers both the types and amounts of payload which must be taken into space and the duration of operations which must be performed in space. Useful payloads for manned lunar and interplanetary operations will be extremely heavy, requiring weights up to millions of pounds. Chemically powered vehicles even as large as Saturn and Nova will fail to provide payloads which permit manned lunar exploration unless the lunar vehicle is assembled from a number of components first established in earth orbit.

Convinced that successful future space operations will hinge on bringing nuclear rocket propulsion into practice, one then may examine where we stand today and what the future may hold for the nuclear rocket.

The present program for developing successful nuclear rockets is represented by the AEC-NASA Rover program. The technical approach employed is the use of a gas-cooled heat exchanger nuclear reactor to heat a propellant gas to a high temperature and then, through a nozzle, discharge it at high velocity.

The heat exchanger type of rocket is simple in concept but to obtain the temperatures necessary to provide the high specific impulse required represents an extension of our present materials technology. Further, an extension in reactor technology is required to achieve high power densities which permit the high thrust-to-weight ratio of the powerplant. Formidable as these problems seem, progress has been heartening. Early experiments with Kiwi type reactors on the ground have already and will no doubt continue to justify faith in this general approach. Also much know-how in the use of hydrogen, the most logical propellant, is being gained by chemical rocket engine developers concomitant with reactor advances.

There seems to be general agreement that the effort to bring the heat exchanger nuclear rocket into being should be pushed as rapidly as the technology will permit.

All space propulsion systems may be conveniently grouped into roughly four classes, each having its own peculiar characteristics and therefore its place in space flight considerations:

1. High thrust at low jet energy.[1]
2. High thrust at medium jet energy.
3. Low thrust at high jet energy.
4. High thrust at high jet energy.

To this point we have dealt with the first two of these classes, the chemical system being of the first class and the Rover type nuclear heat exchanger system of the second. From a long-range future viewpoint the systems which fit into the third and fourth classes may well be the kind upon which sophisticated space operations are dependent. These systems include electric (plasma and ion), controlled fusion and pulsed fission or fusion mechanisms. Thus the subcommittee was briefed on and discussed several of the ideas in these areas.

The essential technique for any electric propulsion scheme is that of producing charged particles of matter and accelerating them to extremely high velocities by electric or magnetic means to gain high exhaust jet energies. These systems are further characterized by low thrust, and therefore, low acceleration and long operating times to gain high vehicular speeds. In turn, however, they may offer great advantages for interplanetary operations because of their payload to total vehicle weight possibilities, and their operational versatility.

Obvious practical problems of reducing electric propulsion schemes to practice at the present stage of investigation include the need to develop highly efficient heat to electricity conversion systems, lightweight and efficient radiator techniques to dispose of waste heat, and lightweight and efficient electromagnetic accelerators. Since practical space electric propulsion cannot be achieved without nuclear heat sources, small fission reactors are being developed for space use. Moreover, in addition to the power supplies the other aspects of electric propulsion systems are receiving the attention of scientists in our laboratories and the practical minded engineers are being awakened to the prospects for such systems and the problems which must be resolved.

Meanwhile, those interested in space electric propulsion and power are keeping a close weather eye on our progress to harness and control the fusion process. For if and when these efforts are successful, we will have an extremely good source of energy for our electric propulsion schemes, of both the low thrust, high jet energy types as well as the pulsed fusion schemes which will give both high thrust and high jet energies. Our space capabilities would be tremendously enhanced by our ability to control hydrogen fusion reactions.

Short of controlled fusion, however, there are other processes which may help us meet the space challenge. One of these is the pulsed fission process represented by Project Orion. Within the limits of security the subcommittee heard of the progress being made on this project.

[1] To distinguish between these, jet energy is not dependent upon the amount of material flowing during a given time but upon the velocity and molecular weight of the moving particles; thrust is dependent upon both mass rate of flow and the velocity of the moving material.

Project Orion employs basically a very simple concept. Mainly the idea consists of releasing small fission bombs from a space vehicle, exploding them outside to give successive propulsive pulses to the vehicle. The problems involved in practical design, such as reckoning with the forces and the radiation produced, are obviously tremendously complicated. So far, however, no theoretically insurmountable difficulties have been encountered. And thus the scientists working in this area continue to be encouraged and believe that the scheme can be reduced to practice.

The latter part of the hearing and discussion by the subcommittee dealt with mechanisms for producing power in space for uses other than that needed for high acceleration vehicle propulsion as such. Progress on employing radioisotopes for space power packages was noted and progress on two fission reactor and conversion systems for space power and upper stage propulsion was examined in some detail. These two systems, SNAP 2 and SNAP 8[2] represent tremendous advances in our attempt to obtain useful electric power in space out of small, lightweight, and economical packages. The nuclear reactor for both of these power packages is basically of the same design and of the same materials, differing only in power output and design detail. Both are epithermal, metal hydride reactors in which the fuel and moderator are homogeneously alloyed.

SNAP 8, which should represent our first useful nuclear reactor application in space, is being designed to give power both for such propulsion operations as changing of satellite orbits and for equipment operation in space. It has a reactor capability of 60 kilowatts when used with two sets of mercury turbine conversion machinery. A good example of its usefulness would include its use with the Centaur rocket in order to change the orbit of a 24-hour communication satellite package launched by Centaur to its required distance of about 22,300 miles from earth. To accomplish this, a small electric propulsion plant such as previously described would be required. A logical extension of this type of application would be a Mars probe wherein the satellite vehicle would be boosted in ever increasing orbital radii to escape velocity, with appropriate scheduling to attain the Mars vicinity.

SNAP 2 has reached a point of successful demonstration of a reactor-turbine system out of which sophisticated, flexible, and versatile power packages can be built. SNAP 8, of course, represents an initial start. Further advances include applications in which the reactor concept can be coupled with a thermoelectric conversion system to substitute a highly efficient and lightweight nonrotating power output mechanism. Basically then, SNAP 2 will result in a family of space powerplants which in turn will give the Nation tremendous advantage in its quest for space leadership.

SNAP 1 is completed and available for certain applications. It consists of a one-megacurie source of cerium oxide which operates turboelectric machinery. It was designed for operation at 500 watts for 60 days. It was actually tested for 2,500 hours of operation. The SNAP 1A requirement which follows this and is to be built in about a year is similar to SNAP 1 except that it will be a thermoelectric device designed for 250 watts and to run for 1 year.

[2] SNAP—Systems for nuclear auxiliary power.

Although the subcommittee felt that the major portion of this particular session should be devoted to nuclear power for space employment, it was appropriate to consider prospects for civilian type use of nuclear powered aeronautics systems. Some thought by responsible scientists and engineers has been applied to this subject in context with the understanding of our technological position in chemical jet propulsion some 20 years ago.

The possible areas of civilian uses of aeronautical nuclear flight, of course, can be delineated at present only in general terms. For one cannot completely predict for the future the performance capabilities, the economics, nor the reliability of nuclear powerplants. Nevertheless, the broad advantages of concentration of energy in lightweight and small volume long-lived fuels can be foreseen in terms of such parameters as payload-to-fuel, payload-to-total-weight, and payload-to-time-and-range on a global scale.

The basic problems associated with civilian-type employment of nuclear propulsion are well known. Certainly the radiological safety problem is well understood but difficult to reckon with. From an economic point of view it is certain that the necessity of radiation shielding will represent large costs in terms of payload and gross weight. And although costs of nuclear powerplants and fuels can only be assumed, there may well be a break-even range between chemical and nuclear powerplants of some 2,000 to 5,000 miles for typical aircraft grossing 500 tons carrying about 200 tons of payload.

The conclusion one may draw about these considerations, then, is that from a global economic viewpoint and assuming that suitable methods of radiation protection can be found, nuclear aircraft can well become a logistic competition, both in terms of cargo and passengers. It is not being overly visionary to suppose that sufficient engineering know-how will accomplish this, just as chemical jet propulsion is now reaching logistic maturity.

E. DIRECT ENERGY CONVERSION AND SOLAR ENERGY SYSTEMS

This session of the frontiers hearings covered the various energy applications and uses which may be derived from nuclear and solar primary sources. A comparison of these advanced concepts is made for future guidance in their exploitation for the use of mankind.

Direct energy conversion

The research for this process is directed primarily toward utilization of nuclear energy although the energy conversion of chemical and solar and various other energy combinations is also appropriate. The term "direct conversion" as used here means the direct transfer of heat energy to electrical energy without the need of a working medium such as a turbine generator or a secondary fluid. Such processes of interest as solar cells, thermoelectricity, thermionic diodes, and fuel cells are illustrative of the kinds of approaches being investigated.

Some of the characteristics common to all these energy conversion processes are:

1. All produce direct current.
2. Regulation and part-load efficiency present problems.
3. Design versatility is good.
4. All are static systems.
5. Efficiency is independent of size.

The latter characteristic was indicated as likely to be the most significant.

The most highly developed cells today are the solar cells using radiative energy or sunlight. Silicon wafers are the most common example of these. Theoretically, 25 percent of the incident radiation can be converted to electricity and in special cases probably about 40 percent. In the laboratory a capability range of 10 to 14 percent efficiency has been reported.

Another heat conversion process receiving much attention now is thermoelectricity. The simple thermocouple is the common everyday example of this. A thermocouple being two metals, one of whose junctions is kept at a fixed temperature. The voltage measured in the circuit allows one to determine the temperature of the other junction. Advances in this relatively old discovery have been made by using semiconductor materials such as lead telluride to provide higher voltages and currents than realized heretofore. Theoretically, efficiencies of about 35 to 40 percent may be achieved.

Thermionic emission is also a process which has been known about for some time. Edison discovered this principle which since has been applied extensively to radio vacuum tubes. This basic principle is now being investigated for power production purposes. It is necessary to have large numbers of electrons flowing from a hot cathode to a cold anode to generate power. Minimization of such effects as that of space charge, cathode temperature, etc., are present objectives. Theoretical efficiencies of about 40 percent have been calculated and efficiencies in the range of 2 to 13 percent have been obtained experimentally.

At Los Alamos work is proceeding on the cesium plasma diode which is called a plasma thermocouple. This was initiated under the Rover program but is now separated from it. In principle the device is simply a plasma which is composed of cesium ions and electrons brought to this state by a heat source (reactor), a cool collector to pick up the electrons from the plasma, and an external connection to return the electrons back to the plasma.

Nuclear fission can also provide energy at a very high temperature. Uranium carbide which is refractory has a melting point of above 2,000° C. and is a good conductor of heat and electricity. It may be quite useful for the plasma cell application. Since it is said to be the best electron emitter known today, its use as the return electrode for the thermionic cell is suggested. Much work on the mixtures of uranium carbide with other carbides must be done to learn their properties and to develop a material with an adequately long lifetime.

The nonnuclear continuous fuel cell seems to hold the most promise for high efficiency. It is not a heat engine but a battery and is limited only by chemical reaction principles. Theoretically, it has nearly 100 percent efficiency and 95 percent has been attained experimentally under special laboratory conditions. A simple example of this device consists of hydrogen and oxygen continuously flowing through porous carbon rods reacting in an electrolyte to form electricity and water.

A number of possibilities exist for using chemicals in fuel cells, among which is conventional petroleum products and air as fuel. Catalysts in the electrodes would separate hydrogen from these hydrocarbons and oxygen from the air for the reaction to produce electricity. Such cells have demonstrated efficiencies of about 35 percent at low tempera-

ture and up to 75 percent at higher temperatures. An efficiency of 60 percent is considered a very reasonable goal and could double the life of the fossil fuel reserves.

Solar energy systems

Solar energy reaches the earth at a rate equivalent to 1,000 kilowatts per acre or about one-fourth of a kilowatt per square yard. From this it is concluded that, despite the large amount of raw energy available for man's foreseeable needs, large surfaces or collectors are needed for conversion of this energy. The variable nature of solar energy presents a problem in most applications. The high investment requirement per unit of energy delivery capacity is probably the most formidable problem. The raw energy is free, but the conversion expense is largely in the equipment investment.

About one-fourth of the U.S. energy consumption is for space heating, therefore domestic solar heating is an extremely worthwhile prospect. A typical requirement for an average house in a sunny climate would be about 500 square feet of solar collector and a heat storage of 1,000 gallons of water or its equivalent.

Solar energy collection in a sunny climate for about $2 per square foot of collector could be competitive where fuel costs more than $1 per million B.t.u. Present solar equipment costs more than $5 per square foot. All present experiments involve a dual system which includes a solar heating system with an auxiliary fuel system. This is desirable since with severe weather spells to consider in designing solar heating systems it would become disproportionately large and therefore uneconomic.

Solar energy for cooking is also being investigated. This requires much higher temperatures than for space heating. Refrigeration and air cooling are also being considered as possible applications.

There are two distinct types of solar power applications; namely, large scale or central station electric power, and small electrical or mechanical power installations. Efficient generation of electricity by solar energy is much more difficult than the use of solar energy for space heating.

1. *Large scale central station power.*—Using a flat plate collector, heat losses are increased at higher temperatures. Poor turbine efficiency accompanying low pressure steam limits the overall conversion efficiency to about 5 to 10 percent. An alternate method is to use a large focusing system to permit generation of high pressure steam for higher efficiencies, although losses in the optical (reflector) system along with the more expensive apparatus also have limitations. The latter method, due to its cost, is considered primarily for small power units of a few kilowatts capacity. Large powerplants could be multiples of small units.

At a presently optimistic investment of $5 per square foot of reflector surface and assuming this figure would cover all other auxiliary costs, the 20 to 40 kilowatt-hours a square foot might produce in a year in a sunny climate would have a fuel cost equivalent of over 1 cent per kilowatt-hour.

In comparison with an average fuel price of 0.3 to 0.4 cent per kilowatt-hour generated in the United States it indicates that large scale production of electricity by solar energy with the focusing system is still distant. The principal efforts with focusing systems are now directed toward small scale power generation.

Preliminary economic studies of large scale power generation by flat plate collectors show amortization of required investment costing several cents per kilowatt-hour. Estimates have shown that U.S. fuel costs would have to rise by a factor of 2 or 3 before solar energy could be economic.

2. *Small scale power generation.*—(Capacity range of a few watts to a few kilowatts.)

Private consumer units are to be assumed here without transmission of electricity being involved. Types of systems suggested here are:

(*a*) Photoelectric generators: These are of the so-called solar battery type using silicon wafer semiconductors. One kilowatt of daylight capacity requires 100 square feet of silicon cells costing over $100,000. Conversion efficiencies of 10 to 15 percent are presently attainable. This approach is expensive and justified only for very special applications.

(*b*) Thermoelectric generation: This follows the well-known thermocouple principle of a heated junction of two different conductors causing a current to flow. At temperatures near 1,000° F. the efficiency of the newer thermoelectric systems can be as high as 10 percent.

(*c*) Thermionic power generators: This is the principle of the electron vacuum tube where a hot cathode causes a flow of electrons to an anode and through an external circuit. Efficiencies in the 20-percent range may be expected although the 4,000° to 5,000° F. temperatures require high mechanical precision in the reflector for attainment of efficiencies in this range.

(*d*) The hot air engine: The Stirling engine is illustrative of this type. Air is heated and cooled alternately by movement back and forth within the engine itself and the resulting pressure changes move a piston. Comparatively high efficiencies can be attained if high enough temperatures can be maintained.

Conclusions

1. The hearings clearly showed that our scientists and engineers have the ideas and the vision necessary to illuminate the frontiers of atomic technology which must be conquered to maintain technical leadership. Many promising long-range applications of nuclear energy which have the potential for contributing to the knowledge and welfare of mankind were identified by the scientists and engineers who testified.

2. The primary problem appears to be the lack of sufficient long-range planning, particularly in the selection of projects. There is a need for periodic examination of advanced, long-range technological applications arising from advances in basic science. The best people at Government, university, and industrial laboratories should be encouraged to devote time to the formulation of advanced applications of nuclear energy and the selection of the most promising concepts for development. A periodic examination and review of such possibilities by both informal and formal means is desirable.

3. Projects aimed at delineating the feasibility of new applications of basic principles and at developing the necessary technology should be encouraged. The AEC laboratories and universities have a particularly important role to play in the early stages of feasibility in-

vestigation of an advanced concept. Further development of promising concepts could be carried forward at Government and university laboratories, together with industry when feasibility is adequately demonstrated. Programs in imaginative development of new areas should be emphasized.

4. It is recognized that many new technological developments in certain fields of atomic research are the result of work undertaken to meet requirements established by the military and NASA. However, work on advanced applications should not be limited to or restricted by developments involved in attempting to meet such requirements. Particularly in the early feasibility investigation stages, work should be carried out which holds promise for advancing the technology even though no immediate value or application can be assigned to the concept.

5. Testimony also brought out how closely universities and industrial organizations work with the scientists of our AEC laboratories in the study and investigation of new applications of atomic energy. The importance of this cooperative effort should be recognized and every effort should be made to assure its continuance. Since the developments under discussion involve major technical and scientific challenges it is particularly important to assure the utilization to the maximum extent possible of the talents of personnel at our best colleges and universities in the development of these advanced concepts.

6. The testimony indicated that current funding for most of the frontier projects discussed was adequate. Some problems were noted on lack of funds of modest amounts for very advanced projects on the one hand (e.g., solar energy development) and projects at later stages of development which require large outlays for continued progress (such as the Rover program). Perhaps the greatest problem observed was the need for long-term assurance of funding of promising projects, rather than year-to-year budgeting.

7. Regular management and technical reviews under the executive branch of the Government are required to assure our success in the development of advanced applications of nuclear energy. The Joint Committee on Atomic Energy of the Congress also intends to hold hearings periodically to assure that the work is properly integrated into the thinking of the Congress and receives the necessary support of the Government.

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